Report of NSTX Program Advisory Committee
(PAC-27)

February 3-5, 2010

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1. Introduction

The NSTX Program Advisory Committee (PAC) held its 27th meeting at the Princeton Plasma Physics Laboratory (PPPL) during February 3-5, 2010. This PAC meeting followed the DOE/OFES Research Needs Workshop (ReNeW) of last year and the more recent CD-1 submission by PPPL for the NSTX Upgrade. Fittingly, therefore, the purpose of this meeting was to give advice and to comment regarding the NSTX research plan as it pertains to (1) preparations to exploit the capabilities of the NSTX Upgrade and (2) the research balance and focus relative to the ReNeW theme areas.

The PAC was charged to answer two questions regarding the NSTX research plan:

1. Does the research plan optimally support preparation for the implementation and exploitation of the NSTX Upgrade Project?

2. Does the NSTX research plan provide proper balance and focus relative to the five ReNeW theme areas: (i) Support of ITER high-priority research needs, (ii) High-performance steady-state plasmas, (iii) Plasma material interface research, (iv)

Advancing the ST as a candidate Fusion Nuclear Science facility, and (v) Optimizing the ST as an alternative magnetic configuration and supporting basic toroidal plasma science?

The NSTX Team presented their research plan to the PAC in 14 presentations over two days. These included a summary of accomplishments from the FY 2009 run, an overview of the FY 2010 run plan, an overview of the NSTX program including upgrade plans, an overview of the facility and diagnostic installation plan, and detailed descriptions of the experimental plans for eight topical science groups (TSGs). The PAC is grateful for the clear and informative presentations delivered by all participants. We appreciate the many references to prior PAC recommendations and the efforts made by the NSTX Team in addressing these recommendations.

The PAC commends the NSTX Team for a tremendously productive FY 2009 run period. NSTX achieved more than 84 run days (exceeding its target) with more than 95% of discharges deemed successful. The NSTX Team completed all program milestones, contributed to more than two dozen important ITPA/ITER-relevant physics topics, and published more than 50 peer-reviewed articles including six in *Phys. Rev. Letters*, 11 in *Nuclear Fusion,* and 11 in *J. Nuclear Materials*. NSTX was recognized as a world-class facility for MHD research as evidenced by the *2009 Nuclear Fusion Award* given to Dr. Steve Sabbagh and his co-authors for the quality and impact of the paper entitled "Resistive wall stabilized operation in a rotating high-beta NSTX plasmas." The NSTX experiment also had numerous operational and scientific successes: routine use of lithium deposition, commissioning of the new HHFW antenna grounding, plasma beta feedback with NBI modulation, the use of upper PF coils to limit arcing during coaxial helicity injection (CHI), reduction in radiated power and impurity content using ELM pacing and a "snowflake" divertor, and the establishment of a vigorous Li physics research group.

The PAC also notes that the NSTX Team continues to be a truly national research effort with significant research lead by collaborators, very strong contributions to ITER-relevant tasks and to the ITPA activities, and strong collaborations with C-MOD, DIII-D, MAST, and JET experiments. The PAC was pleased to see new post-doctoral scientists involved with NSTX, younger scientists serving in task leadership roles, and the coupling of theory and modeling into each research task group. The PAC also congratulates Robert Kaita, Dick Majeski, Lane Roquemore, and Leonid Zakharov for receiving the Kaul Prize for lithium research and for their work with the LTX experiment at PPPL. The PAC is pleased with PPPL leadership in their coordination of Li research within the lab.

Before answering the specific charge questions, the PAC wishes to express again its continued strong support for the NSTX Upgrade Project. The upgrade is the natural progression of the NSTX program. The upgrade will significantly lengthen the NSTX pulse length and provide a renewed facility for exploration of both the ST concept and fusion-relevant magnetic confinement. The new central solenoid provides NSTX with longer pulse discharges that will be key for investigation of steady-state ST scenarios. With the installation of the second neutral beam line, the NSTX facility will gain the capability for off-axis current drive and the additional power needed to investigate higher performance discharges at higher current, current ramp, and ITER-scale divertor power flux. We do urge continuing focus/planning on minimizing the upgrade related downtime, and maximizing staff research activities during the upgrade process.

In the remainder of this report, the PAC presents answers to the two specific charge questions and makes several observations and recommendations pertaining to the eight topical science groups (TSGs) and research thrust areas.

2. Specific Comments Pertaining to the Two Charge Questions

The PAC makes the following comments pertaining to the two charge questions.

1. *Does the research plan optimally support preparation for the implementation and exploitation of the NSTX Upgrade Project?*

   The PAC supports plans for the NSTX Upgrade and is not aware of any implementation concerns. However, the PAC is concerned that the full capability of the upgrade may not be exploited because of divertor, impurity, and particle control issues. The PAC recommends that both the near- and mid-term research plans be modified to give increased emphasis to activities that build confidence that NSTX has a viable divertor-boundary solution that (i) controls particle and impurity influx, (ii) manages divertor heat flux (peak and integrated), and (iii) meets performance targets. While the divertor-boundary physics learned will be essential for the NSTX upgrade, these research results also contribute to overall fusion research goals. Additionally, NSTX has an opportunity to establish the physics basis and understanding for Li pumping with a fully toroidal Li surface and to study high heat flux and long-pulse conditions.

   The PAC offers several suggestions that may help in your increased emphasis on divertor-boundary physics. First, because there will be only limited opportunities for hardware modifications during the next two years, the PAC encourages you to plan ahead for the need for possible minor modifications to address critical divertor physics needs. Consider additional ways to supplement divertor diagnostics (*e.g.,* additional camera coverage and impurity source diagnostics). Additionally, since the LLD/Li systems are your primary option for density and impurity control, more effort and planning is needed to develop an alternative if the LLD fails to perform as expected. As part of this effort, to control impurities the PAC supports the plans to install sample molybdenum divertor tiles to gain experience with Li-coated Mo tiles and its effect on carbon impurities in NSTX.

   The PAC urges the NSTX Team to demonstrate density and impurity control, within the next two years, in discharges characteristic of your post-upgrade operation. We suggest you consider combining the forces of several physics tasks groups to address these critical divertor and boundary issues. For example, the "Advanced Scenarios and Plasma Control" (ASC) Task Group could add to the boundary and Li task groups to strengthen the integrated understanding of the LLD and the effects of Li on discharge behavior.

   The PAC believes the NSTX Team should identify quantitative goals for pumping and impurity control, both short-term (e.g. before the Upgrade) and long-term. Achievement of such targets would build confidence in the divertor solution for high-power, long-pulse post-upgrade NSTX discharges and the ST concept. These targets might specify the density maintained with LLD pumping, the characteristics of an "ideal" LLD (*e.g.* an LLD that is supplied Li directly rather than spraying 90% of the Li around the vessel, and an LLD that allows for the strike point to be on it.) With regard to impurity control quantitative goals could include the divertor heat flux limits, quantification of the level of core impurities and impurity sources as well as source mechanisms.

The PAC also suggests that the NSTX team identify other discharge and physics targets that will optimize operation of NSTX past the Upgrade. These include control metrics related to shaping, low internal inductance, and RWM control.

Finally, the PAC reinforces your plans to give priority to measurements and experiments that will become excluded in the post-upgrade configuration. These include the experiments using the high-k_r microwave scattering diagnostic and the scaling experiments to very low aspect ratio.

2. *Does the NSTX research plan provide proper balance and focus relative to the five ReNeW theme areas: (i) Support of ITER high-priority research needs, (ii) High-performance steady-state plasmas, (iii) Plasma material interface research, (iv) Advancing the ST as a candidate Fusion Nuclear Science facility, and (v) Optimizing the ST as an alternative magnetic configuration and supporting basic toroidal plasma science?*

   The PAC believes the NSTX research plan well addresses the ReNeW research themes areas. With NSTX involved with 14 of the 18 ReNeW thrusts, the NSTX research program does not neglect any of the relevant themes and thrusts. However, the PAC recognizes that NSTX must take leadership for advancing Thrust 16 ("Develop the spherical torus to advance fusion nuclear science"). Furthermore, NSTX should identify and exploit high-leverage research areas where NSTX has unique capability. Clearly, one such area is Li divertor and boundary physics.

   Additionally, the PAC believes a high priority goal of the NSTX research program for the next two years is to build confidence in the capabilities of the upgraded NSTX facilities. Consequently, the PAC suggests that those ReNeW theme areas related to divertor and boundary physics should be strengthened even if this results in some delay to your progress addressing core-specific research theme areas.

3. Comments and Suggestions Pertaining to Topical Science Groups

In addition to the observations and comments related to the specific PAC charge, PAC members have reviewed the plans for each of the Topical Science Groups. Specific and technical comments have been prepared for each Topical Science Group, emphasizing the FY 2010-2012 run periods.

3.1. Boundary Physics

This year the NSTX team provided separate presentations on general boundary physics and lithium-coated divertor operation. The groups and topics involved have obvious overlap. Our PAC report follows this same division.

The Boundary Physics Program has once again made substantial advances in a number of areas during the past year. Highlights include: the determination, during H-mode discharges, of an inverse scaling of scrape-off-layer width (as measured at the divertor plates) with plasma current, and concurrently finding insensitivity of the SOL width to other parameters; the development of optimized ELM triggering via either n = 3 RMP coils (demonstrating reduced ELM size with increased ELM frequency); the demonstration of ELM-free H modes due to density profile modification associated with lithium operation; and first-in-any-tokamak real-time detection of carbon dust (with an electrostatic detector). The NSTX boundary physics team has developed a plan for the next three years that logically builds on these successes.

With regard to the PAC's charges: Clearly the ability of the boundary plasma and the divertor system to handle the heat load and particle inventory is a prime issue for the planned upgrade. The increased attention to the boundary physics and divertor area in general (as measured by the increased fraction of run time this past year, and addition of postdoctoral staff) and to the particular areas of SOL width scaling, snowflake and other flux expansion techniques, understanding of fueling, recycling, and impurities, and dust dynamics indicates that the team is indeed responding in an appropriate way to the challenges of the upgrade.

At the same time, the boundary physics team's research is directly responsive to at least four of the five identified ReNeW theme areas (all except, possibly, high-performance steady-state plasmas, although since a viable power and particle control solution is needed for steady-state operation as well, arguably all thrust areas are addressed). The PAC believes that there is no need to readjust boundary-plasma physics activities to somehow shift the balance of attention on ReNeW themes, particularly given the immediate needs of preparing for the upgrade.

The PAC makes the following suggestions for the boundary area:

- Get more people involved, perhaps by having some redirection/merging of effort from other NSTX topical areas (such as scenarios and control) or possibly from outside of NSTX. This area is sufficiently critical to the success of NSTX-Upgrade that additional effort is justified.
- Deploy the new Thomson channels as soon as practical to shed further light on SOL profiles.
- Develop a means to diagnose the width in the main SOL to check its currently assumed relationship to the measured width at the divertor.
- Look for correlations of SOL width with turbulence levels and other SOL characteristics.
- For discharges with blobby edge transport, further quantify where the particles and power go, and what is the resultant surface response. It would be best if this were a coordinated effort between experiment and modeling, for example, BOUT simulation coupled with post-processing of the fluxes onto the walls with a wall code.
- More generally, determine the fraction of power and particles that go to the main wall versus plasma parameters.

3.2. Lithium and divertor physics

FY 2009 has been the culmination of an extended effort to develop lithium as a plasma-facing surface in NSTX. This is the first extensive use of lithium in a world-class tokamak. The NSTX group is also at the forefront of investigating the application of expanded flux configurations to divertor power spreading with respect to detachment, heat flux reduction, and core impurities/radiation. In particular, they have made an initial demonstration of a stable snowflake divertor configuration with reduced heat fluxes and reduced core impurities. These efforts have demonstrated a sea change in attitude at the NSTX program through increased staff and run time in this area. The added value of the new divertor configurations as well as Li wall coatings on NSTX operational capabilities is clearly appreciated by the other parts of the NSTX program.

Given that the LLD is newly installed, there is no information yet on its pumping capability. The hope is that the LLD will greatly enhance density control through placement of the strike point some distance inboard from it and the far SOL ion fluxes that will impact it. A clear plan to measure the pumping by the LLD separately from the rest of the chamber has not been delineated but should be done as soon as possible. One could consider experiments where first fiducial discharges are well characterized with the LLD well coated. Then the LLD is heated (Li removed) and the fiducial discharges repeated – the difference in pumping corresponding to the loss of LLD pumping. Perhaps the group could also derive a measure of the pumping from planned measurements (Ly-α and probes).

An additional concern about the LLD was that the details of where the Li sits on or in the molybdenum mesh are either unknown or were not presented to the PAC. For example, what is the thickness of the Li on the surface? Is it 10s of nm, several times the depth of the implanting ions as assumed for the pumping predictions? Or, does most of the Li wick into the Mo mesh? Do Li wetting experiments on Mo, as done, e.g., by UIUC and by SNL and collaborators, reliably apply to NSTX? The answers to these questions affect the understanding of how to use the LLD in NSTX and should be remedied by offline experiments (if the information does not already exist). An additional question is how multiple Li depositions change the surface – does it build up in thickness or does it wick into the Mo leaving the same thickness.

The NSTX group has just started research into the effects of flux expansion on divertor heat loads. This topic is central to reaching the Upgrade goals of higher powers and longer pulses, both on a basic level (damage to the divertor surface) and on core plasma performance (even with large flux expansion and no assumption of toroidal peaking the surface is predicted to reach temperatures that correspond to carbon blooms and thus enormous influxes of carbon). We are concerned that the diagnosis of heat load uniformity and impurity sources is below that needed to develop strategies for impurity control and reduce hot spots before the machine is upgraded.

As part of the development of strategies for minimizing carbon in the core and concomitant density increase, the NSTX group is discussing replacing some amount of C tiles in the divertor with Mo. The PAC supports such experimentation as part of a general strategy including the expanded flux spreading of heat and the new diagnostics. The Mo surface can reach higher temperatures than C without causing problems for the core. At the same time, the Mo is potentially more dangerous in terms of effect on the core plasma even with lower sputtering yields than carbon, under plasma conditions of high T_e and low n_e, which could be obtained at the inner divertor due to high D pumping by the LLD. Such plasma conditions would lower the sputtered particle re-deposition and allow a higher fraction of sputtered material to reach the core plasma. Also, melting of Mo tiles can be a problem. If Mo tiles are used, they should be installed as soon as possible, probably on a small scale (small fraction of the toroidal circumference) to gain experience. The tiles should be installed where there is proper spectroscopic coverage to determine Mo influxes to be correlated with core Mo levels. In parallel, an improved set of camera views of the 360-degree circumference of the vessel should be installed and followed to determine any hot spots and correlate with C and other impurity measurements in the core plasma. Utilizing the IR camera in 2D mode to evaluate leading edges and peaking factors should be pursued as this will base the extrapolation to doubling the power and 5x longer pulse lengths more on reality as opposed to assuming uniform temperature rises. Additional IR cameras would help in that effort as well. Also, modeling of sputtered Mo transport, prior to installation, would seem highly feasible and desirable.

3.3. Macro-stability Research

MHD research at the NSTX facility is of world-class quality. This is especially the case with RWM research, as evidenced by the *2009 Nuclear Fusion Award* presented for a paper by S. Sabbagh and co-authors. Work towards a 'unified RWM picture' on NSTX, DIII-D and JT-60U is very important in establishing the scientific base for future experiments and also to give confidence for the assessment of RWM stability in NSTX-U. It is important to continue work on the effects of fast particles and multi-modes for RWM stability.

In considering the first charge question, the PAC believes the improved physics understanding of high-beta and MHD phenomena on NSTX should be used to assess RWM stability in the planned NSTX-U scenarios. Experiments towards lower l_i and V_ϕ should be foreseen in 2011/12 in preparation.

Work in the areas relating to other ITER high-priority areas (*e.g.* disruptions, NTMs) is focused on NSTX specific needs. The team is encouraged to assess even better the area(s) in which they can make unique contributions towards ITER needs in MHD, such as NTM thresholds, NTM excitation, and similar physics areas.

The PAC observes that ELM research is spread over at least three groups (boundary, MHD and Integrated scenarios). Because of the central importance of ELM research, the PAC suggests that the NSTX Team should make sure ELM studies are well coordinated, possibly by appointing a "research organizer" for ELM research.

3.4. Turbulence and Transport

The NSTX program on turbulent transport is very successful thanks to a vigorous effort for improving existing diagnostics and developing new ones. The most prominent tools are a high-k microwave scattering diagnostic, a BES measurement that should be fully operational in 2011 and a multi-channel SXR diagnostic that will operate in 2010. This comprehensive set of diagnostics is of great help to clarify a number of issues, in particular the nature of turbulent electron transport, the origin of momentum transport, the mechanisms underlying particle and impurity transport, and the dynamics of internal and external transport barriers.

In 2009, significant progress was made on several of these topics. First, it has been shown that the improvement of confinement with Lithium operation is due to a local decrease of the electron heat diffusivity. This clearly answers a PAC recommendation, though it would be interesting to know more about the reasons why this local improvement occurs. Second, the high-k reflectometer measurements have clearly shown that the phase velocity of fluctuations is in the electron diamagnetic direction in the rest frame, in accordance with linear stability analysis for ETG modes. This observation confirms that these modes are likely responsible for turbulent transport in NSTX in plasmas without strong Alfvènic activity. Also, negative magnetic shear has been shown to stabilize ETG modes. This property offers new opportunities for the NSTX program. Finally, it has been observed that the electron heat diffusivity degrades in the core when GAE modes become more active, thus explaining why the electron heat diffusivity is above the neoclassical value near the magnetic axis.

The near-term program will continue to investigate the respective role of different candidates (ETG, microtearing modes, and GAEs) to explain electron turbulent transport. With respect to the planned upgrade, it would be interesting to see the parametric dependence of the observed ETGs and GAEs on B_t and I_p to see if the different confinement scaling can be related to the proposed transport mechanisms. This task should be made easier with the operation of new diagnostics. There is no doubt that the measurement of low-k fluctuations with BES will bring new and interesting results, in particular regarding the role of ITG turbulence in ion heat and momentum transport. However, it appears that the high-k microwave scattering diagnostic will be removed due to the installation of the second neutral beam injector during the Upgrade. The PAC strongly encourages the exploration of possible replacement solutions. Indeed, it is likely that high-k fluctuations will play an important role in the confinement of NSTX-U plasmas.

The work that has been done on the L-H transition is interesting, in particular regarding hysteresis and the parametric dependences of the power threshold. The experiments that are planned should bring more information, and the PAC looks forward seeing these results. It is of particular importance to go beyond threshold scaling experiments and characterize also the fluctuations in order to understand the triggering mechanism for the transport barrier. Overall, it is certainly important to clarify the issues related to edge turbulence and its interplay with core turbulence, in view of the operation of NSTX with Li-coated PFCs. Regarding this point and the possible implementation of Molybdenum tiles, the PAC recommends intensifying the study of impurity transport and investigating possible solutions (e.g., external coils, RF heating) to prevent impurity accumulation. This task should be made easier with the operation of the new multichannel soft X-ray diagnostic in 2010/2011.

The PAC acknowledges with pleasure the strengthening interaction between theoreticians and experimentalists and the ongoing fruitful collaborations with US and foreign laboratories. The NSTX Team is encouraged to continue to pursue this direction.

3.5. Energetic Particles

The NSTX Team has made good progress in understanding fast ion losses driven by multiple Alfvén eigenmodes. The combination of NOVA-K and ORBIT is a powerful tool to estimate the fast ion losses. By using the full eigenfunctions from linear codes and scaling the amplitudes (and keeping enough modes), they were able to reproduce the level of fast ion losses measured on DIII-D, thus resolving previous discrepancy. The results on simultaneity of GAE/CAE avalanches (higher frequency) and TAE/EPM avalanches (shear Alfvén frequency) are interesting. Nonlinear mode-mode coupling is being explored. Beyond these "pure" energetic particle physics results concerning Alfvén eigenmodes, they have also found important effects of fast ions on RWM stabilization, electron thermal transport, and HHFW operation.

The research plan is well laid out for the next few years. For example, they plan to extend TAE studies, especially of avalanches, to H-mode plasmas in FY 2010-11. The planned diagnostic upgrades will help these studies. For example, the BES diagnostic, to be installed in FY2010, will be a boon to measurement of modes driven by fast particles (*e.g.*, continuum damping by kinetic Alfvén waves). Tangential FIDA (in addition to the existing perpendicular FIDA) will be helpful for looking at how neutral beam ions cause Alfvén instabilities and affect transport.

Also, the LLD, the improved HHFW antenna, and rotation braking will be useful for the studies of energetic particle effects on electron transport, HHFW, and RWM stability.

GAE-driven magnetic fluctuations seem to be correlated with enhanced electron transport. For the same reason, TAE and CAE (and other Alfvén eigenmodes) activity should also be correlated with higher electron thermal diffusivity. An assessment should be made of the impact of Alfvén eigenmodes (other than GAEs) on electron transport.

Identifying the importance of energetic particles on RWM stability in low rotation discharges could result in a breakthrough that might lead to reconciling the DIII-D and NSTX observations. Since the energetic particle population is highly anisotropic in NSTX, modifications of the code MISK to study the effects of anisotropic energetic particles are required.

In general, the energetic particle physics research plan for the next couple of years does not depend very much on the impending upgrade for NSTX. Nevertheless, an important preparation for post-Upgrade operation is to work further on improving predictive capability, especially by validating the linear and nonlinear energetic particle simulation codes. The NSTX Upgrade, with its new center stack and additional neutral beam, will extend parameter capabilities for fast particle studies. A quantitative assessment should be made of Alfvén eigenmode physics for NSTX-U including linear thresholds and fast ion losses. The PPPL linear codes could be used to explore whether stability regime(s) are modified significantly. The M3D-K code could be used to explore nonlinear behavior, since it is self-consistent, whereas the ORBIT code is not.

3.6. RF Heating with HHFW

Significant progress was made in the HHFW area in 2009. This includes: (i) successful upgrade of the antennas allowed operation at 3-4 MW, with less antenna conditioning time, (ii) record $T_e(0) \approx 6.2$ keV in L-mode and $T_e(0) > 5$ keV in H-mode (HHFW only), and (iii) exploitation of HHFW for L-H mode transition studies in He and D plasmas.

The PAC applauds the use of state-of-the-art simulation capability (*e.g.*, the codes AORSA, CQL3D, and ORBIT RF) and also the opportunity presented by the new FIDA diagnostic to validate code predictions, especially finite orbit width issues in the modeling of fast-ion interactions.

The PAC recommends that NSTX continue to push the antennas to find the new limits to antenna performance and develop plasma scenarios that can be used for HHFW heating in current ramp-up and start-up plasmas. These might include: (i) investigating impurity puffing to reduce high-power arcing, and (ii) studying trade-off between outer gap and pulse length with NBI in order to assess options for optimization.

The PAC also suggests that NSTX (i) revisit the absorption and propagation physics of HHFW in NSTX-U in light of the fact that the harmonic resonances will be lower with the 1 Tesla magnetic field for the upgrade, (ii) continue to assess the level of parasitic losses in combined HHFW+NBI experiments, especially now that combined HHFW+NBI heating has been demonstrated, (iii) continue to interact with the Boundary Physics Group to quantify RF sheath losses in NSTX and to aid in developing mitigation techniques if needed, and (iv) evaluate the effectiveness of ELM/arc discriminating electronics to maintain antenna protection in the presence of ELM-induced transients in the antenna loading.

3.7. Current Start-up and Ramp-up

The start-up and ramp-up of the plasma current without the use of a central inductive solenoid has been identified as the highest priority issue for ST research in recent planning processes. The importance of solenoid-free start-up and ramp-up arises because this capability is expected to be essential for a CTF or reactor based on the ST. Two key advances in support of solenoid-free operation in NSTX were achieved during the 2009 campaign. First, the impurity content of plasmas generated by coaxial helicity injection (CHI) was significantly reduced, leading to larger plasma current in a subsequent inductive current ramp. Reduced impurity was achieved primarily by mitigating arcs in the "absorber" region using specialized local field-shaping coils (the "absorber coils"). Second, modifications of the HHFW antenna were completed, enabling the higher power operation needed for current ramp-up by bootstrap current overdrive. Initial results with the modified antenna are encouraging.

The PAC notes that the planned experiments to optimize arc mitigation using the absorber coils are high leverage in informing the expected performance of CHI post-upgrade of the center-stack. Since there are no equivalent coils planned in the new center-stack, the effects of local field shaping in the absorber region need to be understood, and an assessment made on whether CHI will be negatively impacted by the absence of these coils. We also strongly urge the use of the LLD in CHI experiment in 2010, even if experiments with reversed toroidal field are not available. The impact of LLD on impurity and particle control could be very significant. We also strongly endorse the experimental plan to heat lower current target plasmas with HHFW to demonstrate full non-inductive current sustainment. This is likely to greatly simplify issues associated with rf coupling, equilibrium control, and stability. It will also begin to quantify power requirements for the more challenging step of current ramp-up.

The PAC recommends maintaining a close collaboration with DIII-D (and other facilities, as relevant) on outer-PF start-up. This is a very promising path, but no single device presently has the combination of available PF volt-seconds and heating to do both start-up and ramp-up. Perhaps solenoid induction could be used on NSTX to match plasma conditions obtained by outer-PF startup on DIII-D, and then subsequent HHFW heating used for current ramp-up, thus combining methods available in separate devices to demonstrate an effective scenario. The PAC continues to encourage revisiting start-up and ramp-up scenario modeling using realistic inputs from achieved plasma conditions, taking into account transport and stability considerations.

3.8. Advanced Scenarios and Control

The PAC compliments the NSTX Team for the progress made during the FY 2009 run towards demonstration of ST integration goals. These include the following: (i) quasi-stationary high-β plasmas over a range of q_{95} at high κ, (ii) improved density control using Li conditioning, (iii) ELM pacing using $n = 3$ perturbations and vertical jogs, (iv) shape and divertor control at high κ, β and low *li*, and (v) HHFW heating and real-time β_N control.

The PAC believes the 2010 research plans for the Advanced Scenarios and Control (ASC) Task Group are appropriate based on near-term needs. On the longer term, the PAC makes the following suggestions:

- For density and impurity control, the NSTX Team should consider (i) increased emphasis on integration of ELM pacing and high-β operation and (ii) reduction of uncertainties in expectations for density/impurity control in high-performance plasmas, through systematic experiments and improved diagnostics,

- For HHFW, the NSTX Team should consider increased emphasis on determining compatibility of HHFW (in particular plasma-antenna gap) and long-pulse, high-power NBI.

- For modeling, the NSTX Team should reinvigorate efforts to model discharge scenarios through improvements in transport modeling and benchmarking with experiment.

- The PAC suggests the plans for advanced scenarios be expanded to incorporate the performance capabilities of the NSTX upgrade. For example, present plans use only four of six NBI sources, and reach targets of only 0.725 MA at a toroidal field of 0.55 T.

- Finally, the NSTX Team should investigate and develop backup options for density control if LLD is found to be incompatible with long-pulse, high-β operation.

Respectfully submitted,

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